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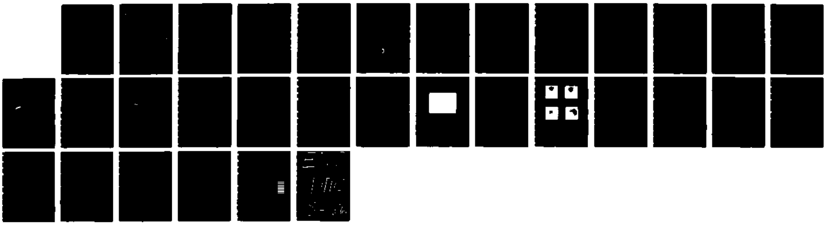

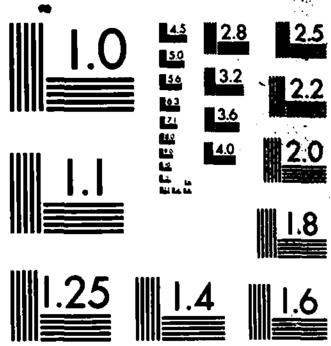

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MEMORANDUM REPORT BRL-MR-3497

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REVIEW ON COMPRESSION IGNITION SENSITIVITY STUDIES OF LIQUID GUN PROPELLANTS

John D. Knapton
Eberhard Schmolinske

March 1986

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US ARMY BALLISTIC RESEARCH LABORATORY
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Most of the past work on the compression ignition sensitivity of liquid gun propellants did not succeed in elucidating the fundamental processes involved in compression ignition. Existing theoretical predictions rely on simplifying assumptions and remain unvalidated until appropriate experimental investigations are made. Recent experimental studies have focused on safety aspects and have tried to define reaction limits based on the ullage present,

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the bubble size, and the pressurization rate resulting in "go or no-go" type of tests. Interestingly, many of the tests have revealed, for cases where a compression ignition event was observed, a finite induction time before there is a significant pressure generation.

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I. INTRODUCTION

The use of a liquid propellant (LP) in medium or large caliber guns makes it necessary to understand the factors which may cause problems stemming from erratic ignition and combustion. The mechanism responsible for these problems has been the subject of numerous investigations. For instance, poor reproducibility in propellant combustion may be associated with the design of the igniter system, pressure oscillations may be the result of combustion instabilities, and uncontrolled ignition sites may be generated due to ullage or bubbles in the LP. Of particular concern in this paper are the bubbles in the LP which may result in propellant burning in the LP reservoir of a regenerative injection liquid propellant gun.

One plausible explanation that emerged from the early studies on bulk loaded guns was that air or vapor bubbles, due to excessive ullage in the firing chamber and brought in during the pre-firing fill process, may become sudden hot spots during the ignition start-up as a result of rapid compression.[1] The observed reaction could be the result of propellant reacting with heated air, a chemical or kinetic sequence quite different possibly from normal thermal decomposition. No data presently exist that could be used to differentiate between these two possibilities.[2]

The use of LP requires the pumping of the propellant at high flow rates during loading. Cavitation can occur in the flow passages, thereby introducing vapor bubbles into the liquid. It has been speculated that the adiabatic compression of such gas and/or vapor bubbles is a major cause of reaction initiations.[1,3-5] If this is indeed the case, one may observe initiation at the numerous bubble sites that may approach, under sufficiently severe pressure loading conditions, simultaneous reaction of the entire propellant sample.

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[1] N. A. Messina, L. S. Ingram, P. E. Camp and M. Summerfield, "Compression-Ignition Sensitivity Studies and Liquid Monopropellants in a Dynamic-Loading Environment," JANNAF Combustion Meeting, CPIA Publication 308, Vol 1, pp 247-284, 1979.

[2] N. Klein, "Summary of the JANNAF Workshop on Liquid Propellants for Gun Applications," 1977, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005-5066.

[3] J.D. Knapton, I.C. Stobie, R.H. Comer, B.D. Bensinger and D.L. Henry, "Evidence of Secondary Ignition in HAN-Based Liquid Monopropellant," Ballistic Research Laboratory IMR 209, June 1976.

[4] R.F. Chaiken, "On the Mechanism of Low Velocity Detonation in Liquid Explosives," Astronautica Acta 17, pp 575-587, 1972.

[5] W.F. Morrison, J.D. Knapton, J. Mandzy, "Progress Report on a Mechanism for the Compressive Ignition of Liquid Monopropellants," JANNAF Combustion Meeting, CPIA Publication 329, Vol I, pp 377-398, 1980.

Extensive evaluations of the sensitivity of Otto-II and the HAN-based LPs to compression ignition have been conducted at the Ballistic Research Laboratory (BRL),[6] the General Electric Ordnance Systems Division (GE),[7-9] the Princeton Combustion Research Laboratories (PCRL),[10-14] and on a preliminary scale at the Fraunhofer-institut fuer Kurzzeitdynamik, Ernst-Mach-Institut, Abteilung fur Ballistik (EMI-AFB).[15,16] From the results of these experiments and theoretical considerations several ignition concepts have been considered. Mandzy et al.[7] stated that it is within the current

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[6] V.M. Boyle and E.A. O'Leary, "Ignition of NOS-365 Liquid Propellant Containing an Air Bubble under Simulated Breech Pressurization Conditions," Ballistic Research Laboratory Technical Report ARBRL-TR-02236, 1980.

[7] J. Mandzy, K. Schaefer, J.D. Knapton and W.F. Morrison, "Progress Report on Compression Ignition Sensitivity of NOS-365," JANNAF Propulsion Meeting, CPIA Publication 315, Vol 1 pp 377-398, 1980.

[8] J. Mandzy, K. Schaefer, J.D. Knapton, and W.F. Morrison, "Progress Report on Compression Ignition Sensitivity of NOS-365 under Rapid Fill Conditions," JANNAF Combustion Meeting, CPIA Publication 329, Vol II, pp 309-327, 1980.

[9] "Liquid Propellant Technology," General Electric Company, Ordnance Systems Division, Annual Report, February 1980.

[10] N.A. Messina, L.S. Ingram, P.E. Camp, M. Ben-Reuven and M. Summerfield, "Compression-Ignition Sensitivity Studies of Liquid Propellants for Guns," Princeton Combustion Research Laboratories, Rep. No. PCRL-FR 79-004, 1979.

[11] N.A. Messina, J.M. Leyzorek, M. Summerfield, J. Mandzy and R.E. Mayer, "Combustion-Ignition Sensitivity Studies of Liquid Monopropellants," JANNAF Combustion Meeting, CPIA Publication 297, Vol I, pp 335-358, 1978.

[12] N.A. Messina, "Compression Sensitivity of Liquid Monopropellants," US-German Visit on Liquid Propellant Technology at Ballistic Research Laboratory under DEA-1060, 1983.

[13] N.A. Messina, L.S. Ingram and M. Summerfield, "Sensitivity of Liquid Monopropellants to Compression Ignition," JANNAF Combustion Meeting, CPIA Publication 347, Vol II, pp 269-287, 1981.

[14] N.A. Messina, L.S. Ingram and M. Summerfield, "Sensitivity of Liquid Monopropellants to Compression Ignition," Princeton Combustion Research Laboratories, Final Report PCRL-FR-83-004, June 1983.

[15] E. Schmolinske, "Bubble Compression in Liquid Propellants," US-German Visit on Liquid Propellant Technology at Ballistic Research Laboratory under DEA-1060, 1983.

[16] E. Schmolinske, Blasenkompression in flussigen Rohwaffentreibmitteln, Symposium, "Innernballistische Leistungssteigerung von Rohrwaffen," BICT, 1982.

state-of-the-art to calculate the average bubble pressure and the average bubble diameter as a function of time, but such an analysis is insufficient to predict the likelihood of ignition occurring under any given set of circumstances. At this point it appears safest to consider theory only as a qualitative guide.

Compression ignition may be a very complex process. In order to identify possible adiabatic compression mechanisms related to erratic combustion during the LPG cycle, to achieve a basic understanding of the compression sensitivity, and to guide further studies, some of the past research work on bubbles or ullage containing LP has been examined. The review will focus on HAN-based LPs, since most of the recent LP research effort in the United States has been done in this area.

II. COMPRESSION SENSITIVITY EXPERIMENTS

The first group of tests with only a single bubble (6 mm diameter) suggested that ignition might occur for high pressurization rates (>6700 MPa/msec). These tests were performed at the BRL.[3] Because of limitations of the test equipment, more detailed test programs were later performed at the BRL using a different test set-up,[6] at the GE Company,[7-9] at the PCRL,[1 10-14] and at the EMI-AFB.[15 16]

The second group of tests at the BRL[6] (Figures 1 and 2) used what is called a setback simulator, or activator, to generate pressure within an LP (NOS-365) containing a suspended air bubble (2 to 6 mm diameter). The activator was fired in both the "impact mode" and the "contact mode." The maximum test pressures were around 600 MPa, except for one of the tests where a reaction occurred which resulted in a pressure > 1350 MPa. The pressurization rates ranged from 25 MPa/ms to about 800 MPa/ms. Because of complications with the test equipment and interpretations of the results, only the conclusions for the "contact mode" are described here and only for the case where the propellant was contained with sealing plugs. The test results[6] showed that the **intensity of the reaction appears to increase with** bubble size, even for the cases where the pressurization rates in the liquid were as low as 26 MPa/msec.

The Ordnance Systems Division at the GE Company performed an extensive series of tests on the compression of the monopropellant NOS-365. The test device has been called the moderate scale tester and uses pistons for compressing the LP.[7-9] The experiments were performed under a variety of conditions: propellant ejection from the tester, propellant confinement by the inside diameter of the tester and a plastic spool, and propellant confinement in a plastic tube. The tests were performed with and without bubbles. In the first group of tests[9] (Figure 3) the propellant was statically loaded and then, during the test, ejected from the fixture. The results are important since ignitions occurred and the source of ignition was never identified. When the propellant was pressurized with a driving peak pressure as low as 100 MPa reached in 1.5 MPa msec, ignitions occurred in six out of the first six tests. The planned propellant ejection from the tester was considered a possible source of ignition, however, other unknown ignition sources may have existed or ignition may even have occurred from flow or leakage past defective seals. In the next group of six tests the number of ignition events was, significantly, reduced to two. For these

tests (Figure 4), the propellant flow was eliminated by using a floating piston/plastic spool arrangement. For the first ignition, the plastic spool had a crack as a result of fabrication. For the second ignition, the spool had been deformed from the prior tests. Therefore, propellant flow still remained a possible source of ignition due to the defective spools. The procedure for confining the propellant was further modified due to the problems with the plastic spool and to provide a procedure for dynamic loading. A floating disc (aluminium) and rod (Lexan) assembly were used to facilitate loading and to provide a water barrier between the liquid propellant and the solid propellant charge. Further tests with this procedure were abandoned due to difficulty in assembly without damaging pressure seals and to the continued possibility of propellant flow into the chamber.

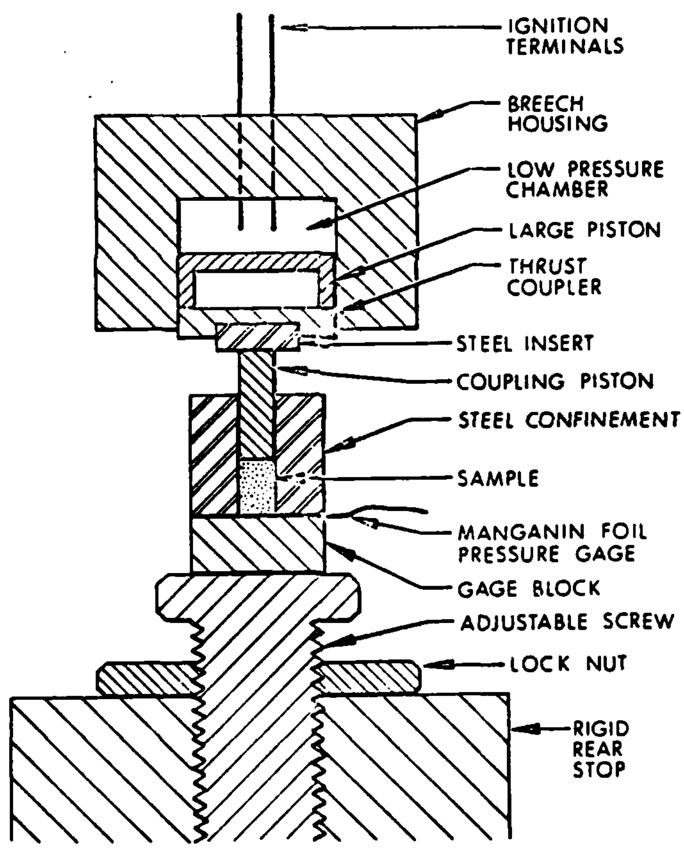


Figure 1. Diagram of the Setback Simulator, or Activator for Testing in the Contact Mode[6]

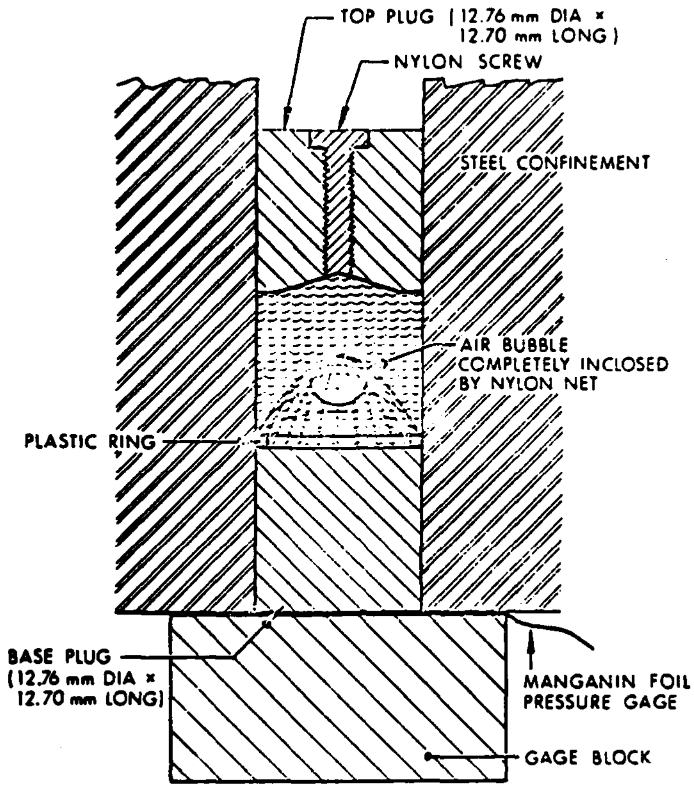


Figure 2. Diagram Illustrating the Method used for Containing the Liquid Propellant in the Activator[6]

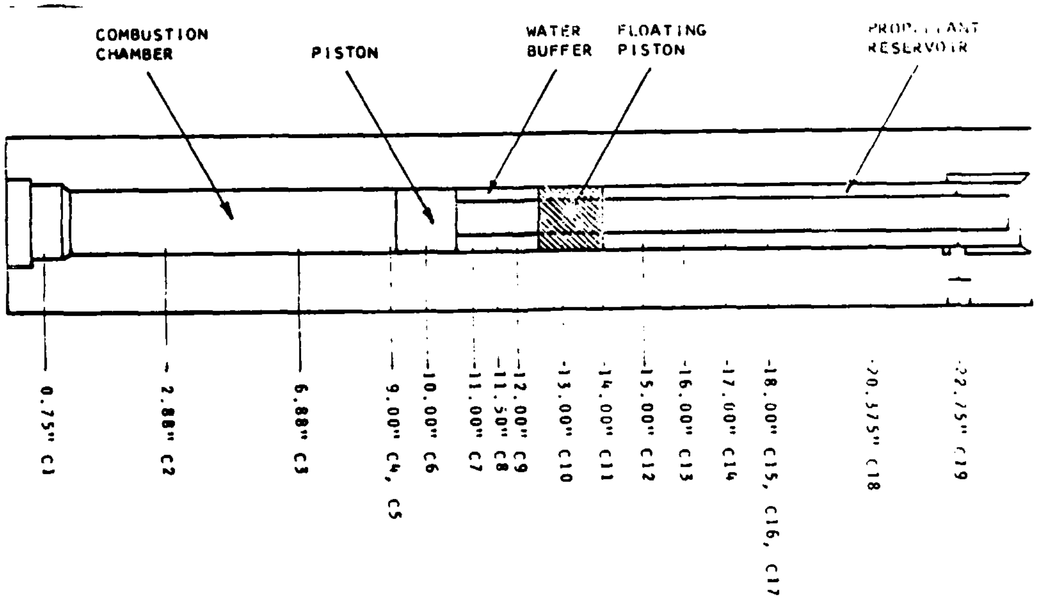


Figure 3. Diagram of the Moderate Scale Tester Used During the Propellant Ejection Tests[9]

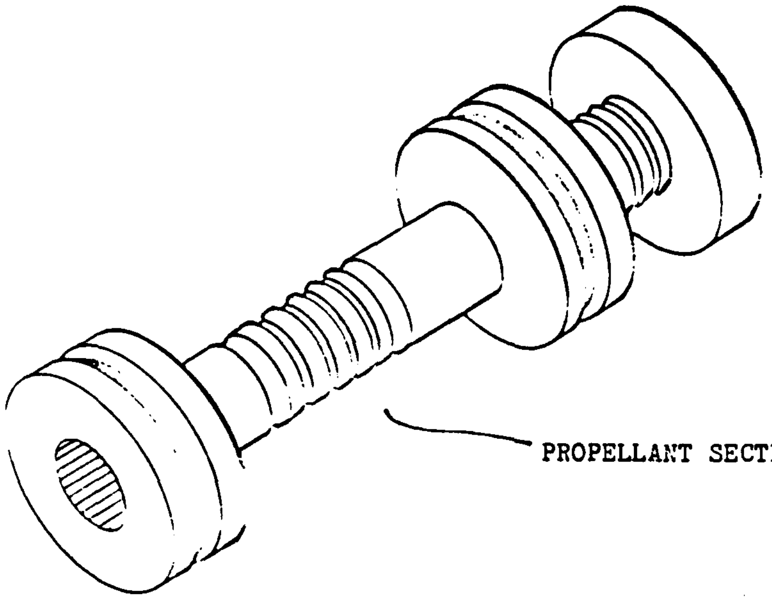


Figure 4. Illustration of the Floating Piston or Plastic Spool Used in the Moderate Scale Tester[9]

A new series of experiments were started in which the propellant was confined inside a plastic container or "squeeze" tube.[7 9] The container, with tests performed with and without bubbles, was immersed in water inside of the test chamber (Figure 5). A total of 34 tests were run under various pressure loading rates and with "neat" propellant and with the propellant containing one large bubble (typically 0.5 or 2 ml). It is important to note, based on similar tests with water, that the single bubble was shattered into smaller bubbles as a result of the pressurization. Thus the condition of the bubble was not known during the test. Unfortunately, the test fixture was not sensitive to the occurrence of an ignition event. Of the 34 tests, there were two definite ignitions and five possible ignitions. It was argued that bubbles on the order of a millimeter in diameter may play an important role in defining the reaction - no reaction zone ,and that the product of the peak pressure and pressure rise rate may be a useful correlating parameter. Despite the uncertainty in the results there were no ignitions when the maximum pressure was less than 340 MPa and when the average rate of pressure rise was less than 550 MPa/msec.

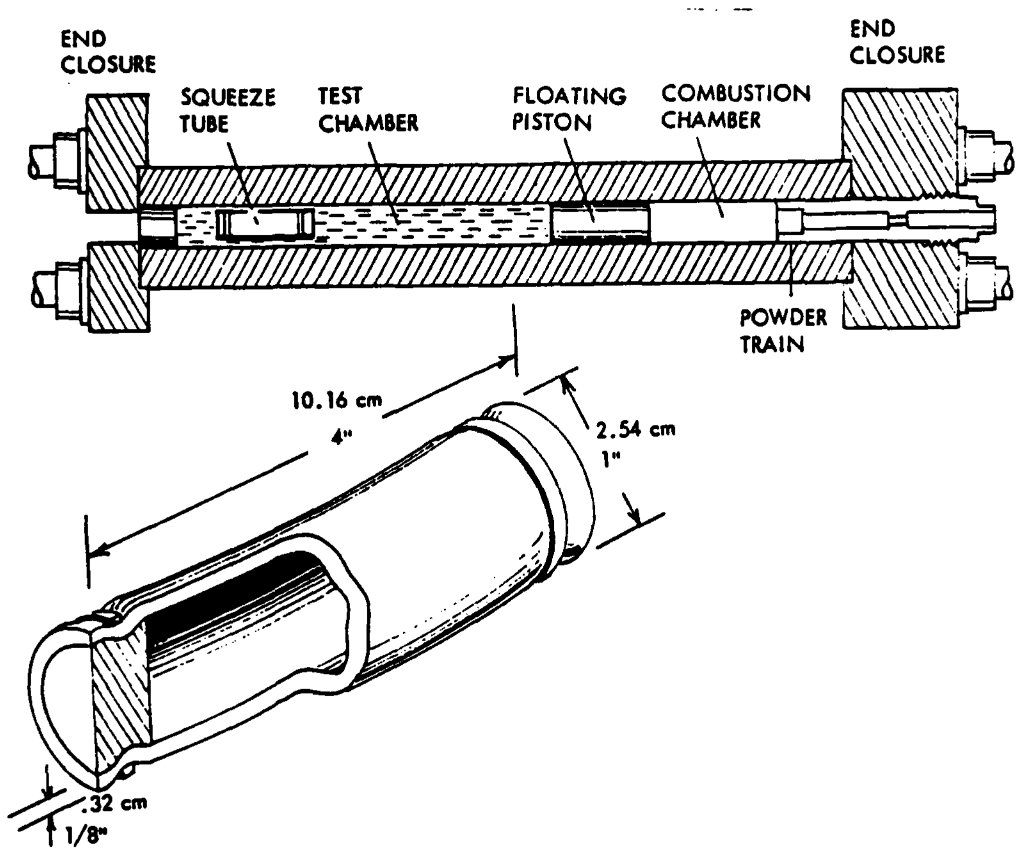


Figure 5. Illustration of the "Squeeze" Tube Used in Moderate Scale Tester[7,9]

A method for dynamically loading the propellant was developed for the fourth group of experiments by the GE Ordnance Systems Division.[8] For these tests (Figure 6) the propellant flow into the tester was carefully controlled to minimize the possibility of cavitation. Both "neat" propellant and propellant with 0.5% ullage were tested. The volume of propellant dynamically loaded was 66 ml (two tests), 22 ml (11 tests), and 54 ml (6 tests). For these tests the prepressurization was 1.8 MPa. Time for loading the 22 ml was less than one second. High speed photographs of the propellant with ullage after injection into a plastic fixture, with a pressure of 0.3 MPa, showed that the ullage appeared to be uniformly distributed with typical bubble diameters of about 0.25 mm. Two pressurization loading rates were used for the 22 ml tests, about 45 MPa/msec and 250 MPa/msec. No ignitions occurred. For the remaining tests, two ignitions occurred, one with 66 ml of "neat" propellant and the second with 54 ml of propellant with 0.5% ullage. The first ignition was characterized by an unusually long delay (18 msec) before there was an indication of pressure rise in the test chamaber. The second ignition apparently occurred in a 138 MPa check valve in the fill line outside of the test chamber and may have been initiated by a failure of the seal on the

high pressure side of the propellant columm. Subsequent tests showed that 35 MPa pressure surges were being sent into the fill line apparently caused by a failure of a seal. Actual causes for both ignition events could not be identified, although ignition by adiabatic compression is a possibility.

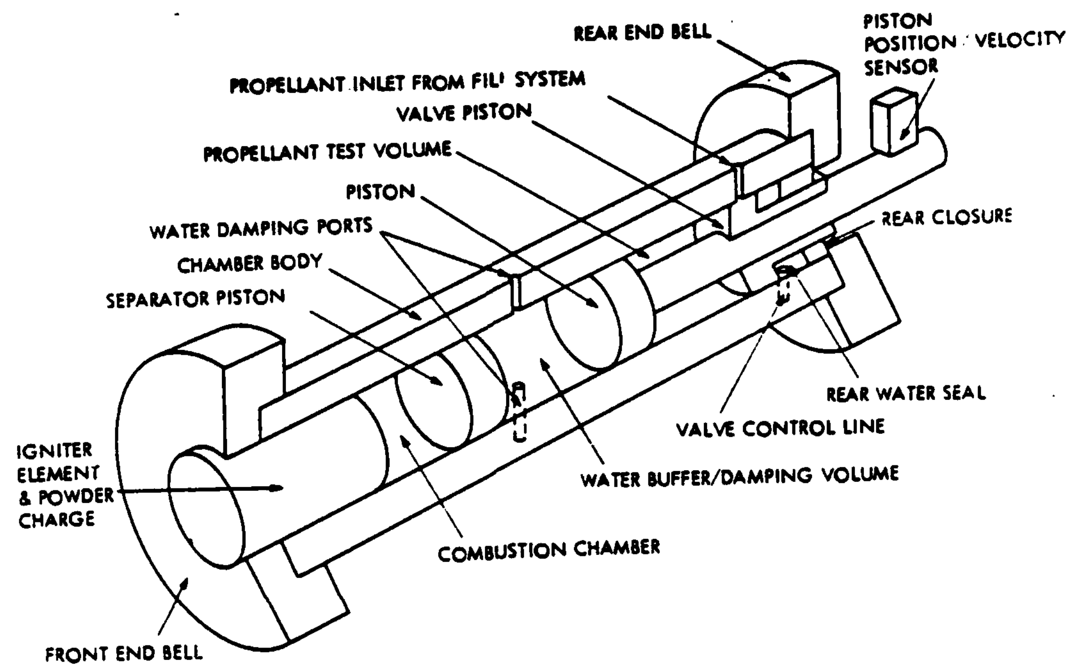


Figure 6. Illustration of the Moderate Scale Tester Used in the Rapid Propellant Fill Tests[8]

PCRL has developed an alternate approach for testing ignition due to adiabatic compression.[1 10-14] The test device (Figure 7) consists of a means for dynamically loading either "neat" propellant or propellant with a known ullage into a 6.65 cm^3 chamber. After the monopropellant is loaded, a solid propellant charge is fired, after a prescribed time delay, in an adjoining chamber to provide a pressurization source for the liquid monopropellant column. The pressure generated in the solid propellant chamber acts on a separator piston which then compresses the monopropellant. Pressure rise rates of about 170 MPa/msec, 310 MPa/msec, and 480 MPa/msec were used for the tests. The first group of tests with NOS-365 were performed with zero time delay.[1 10] Under these conditions, the state of the LP was difficult to identify due to severe pressure oscillations and cavitation imposed on the liquid column. These tests will not be included here. The control of the state of the propellant for the second group of tests was significantly improved.[13] The pressure oscillations were reduced using mechanical damping procedures and a 10 msec time delay was inserted between the loading of the monopropellant and the firing of the solid

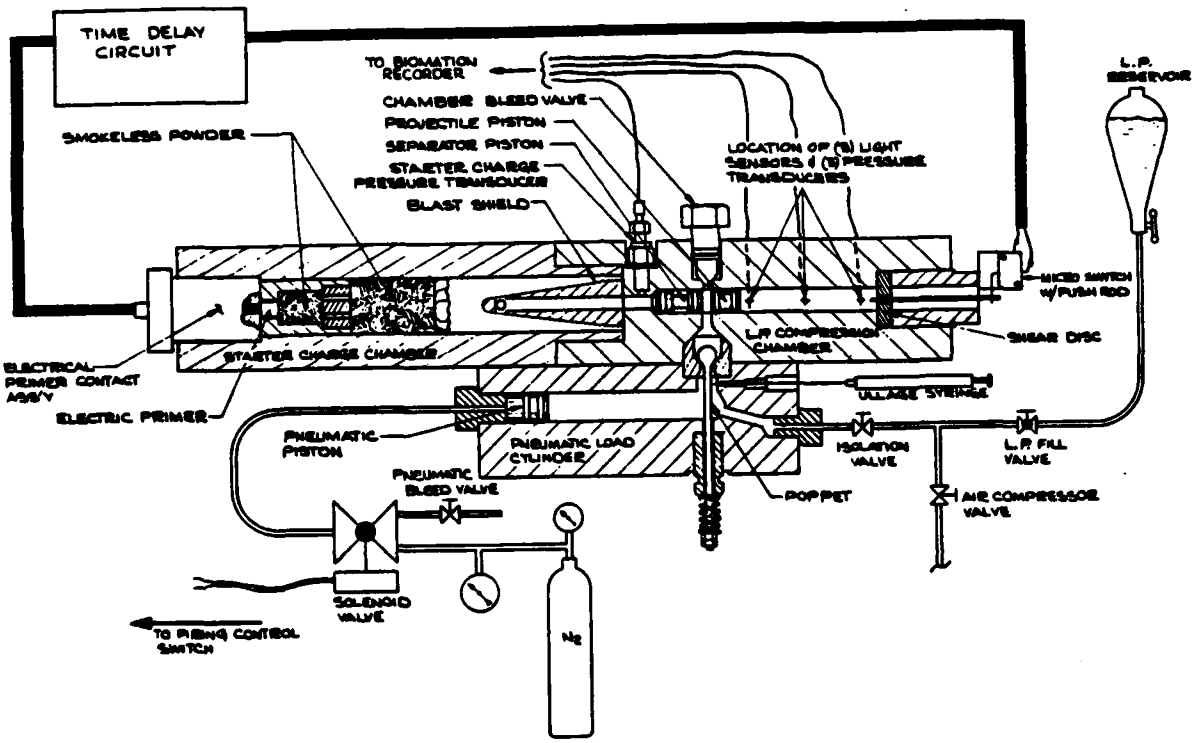


Figure 7. Schematic Drawing of the Compression Ignition Sensitivity Tester (Ref. 13). Propellant is rapidly loaded through the poppet valve and enters the chamber between the separator piston and the projectile piston. The projectile piston is displaced as the propellant fills the chamber. Maximum displacement of the projectile piston occurs when the projectile contacts a wire in the end plug which activates a time delay relay circuit to provide firing voltage to the electric primer in the starter charge chamber (pressurizing source).

propellant charge to produce a prepressurized monopropellant charge at the onset of rapid compression. For "neat" propellant prepressurized to 1.4 MPa and for pressurization rates up to 480 MPa/msec there were no ignitions. For the same pressurization rate but with 3.1% ullage and a prepressurization of 1.2 MPa (the state of the prepressurized monopropellant was a uniform distribution of bubbles with diameters less than 0.025 mm), there were two ignition events out of three tests (Figure 8a). For the same test (same ullage, same pressurization rate) but at a higher prepressurization level of 2.3 MPa (the injection pressure was 3.4 MPa), there were no ignition events out of two tests (Figure 8b). In all, PCRL conducted 26 tests in the second group of tests with NOS-365.[13] No ignition events were recorded with 3.1% ullage and when the prepressurization was 2.3 MPa. Five ignition events were recorded when the prepressurization level was 1.2 MPa and when there was 3.1% ullage, with pressurization rates greater than or equal to 310 MPa/msec. For comparison purposes, the results of tests with 1845, 1846, and OTTO-II are also included in Table 1.

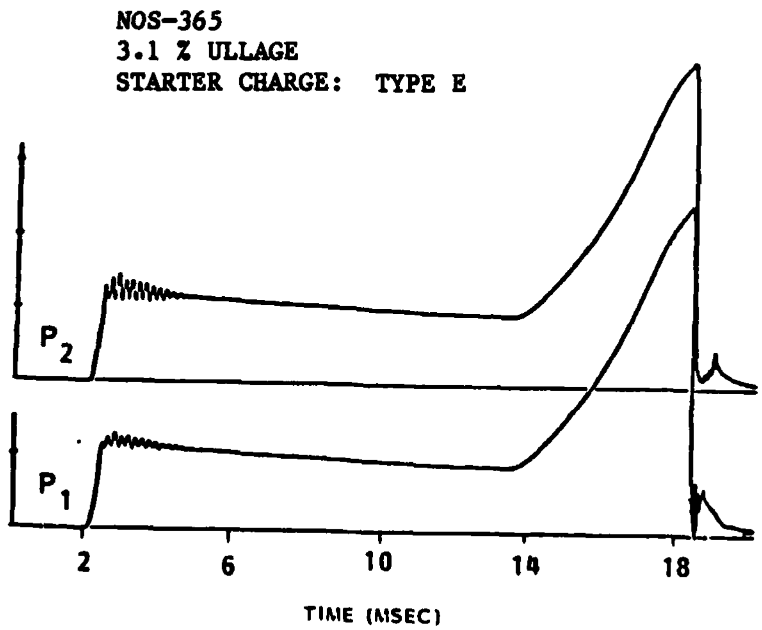


Figure 8a. Illustration of a Reaction for Tests with NOS-365[13]

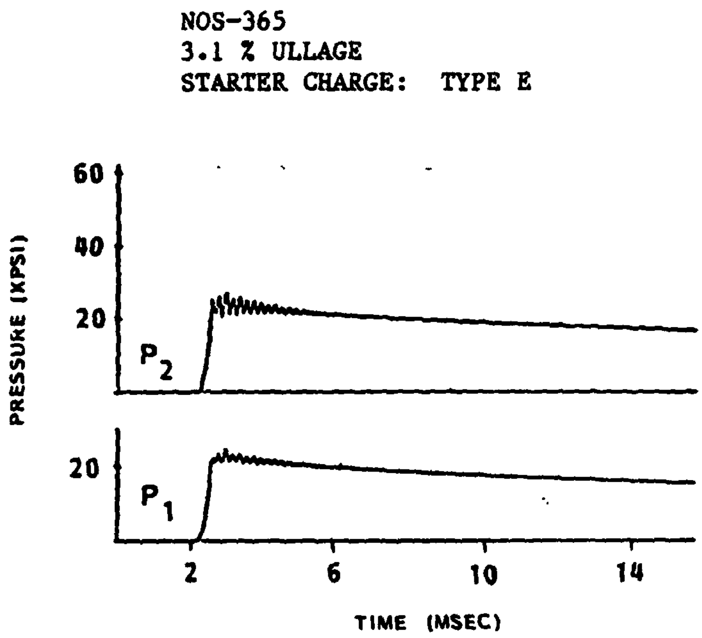


Figure 8b. Illustration of a No Reaction for Test with NOS-365[13]

At EMI-AFB[15 16] research is going on to identify the response of a few bubbles in an LP to a rapidly increasing applied pressure by visualization of the compression event. The test fixture (Figure 9) has a 14 cm^3 test volume and is similar to that of the BRL chamber,[6] but has optical windows for taking pictures with a high speed camera. Tests on water, IPN (isopropylnitrate) and NOS-365 were performed with pressurization rates up to 270 MPa/msec and with various bubble sizes (0.2 mm to 2.2 mm diameter). The percent of ullage was 1.4%. Three tests out of eight on IPN with air bubbles resulted in a reaction, one in no reaction, and in four tests mechanical failure of the windows occurred at 90 MPa. The three cases with a reaction had the following pressure-time histories:

15 MPa within 9 ms followed by a pressurization rate of 45 MPa/ms,
12 MPa within 4 ms followed by a pressurization rate of 90 MPa/ms,
15 MPa within 4 ms followed by a pressurization rate of 80 MPa/ms.

NOS-365 was tested under conditions similar to the three tests with IPN which resulted in reactions. Two tests with NOS-365 yielded no reaction. For these tests, the pressure reached 15 MPa in 3 msec followed by a pressurization rate of 90 to 95 MPa/msec (Table 1). For a test in which there was an initial pressurization rate in the liquid of about 140 MPa/msec there was a reaction (Figure 10). Importantly, the reaction was delayed similar to the observations at GE and PCRL. Because of complications with the high speed camera and the delayed reaction (up to 5 msec), no pictures were recorded showing the ignition event.

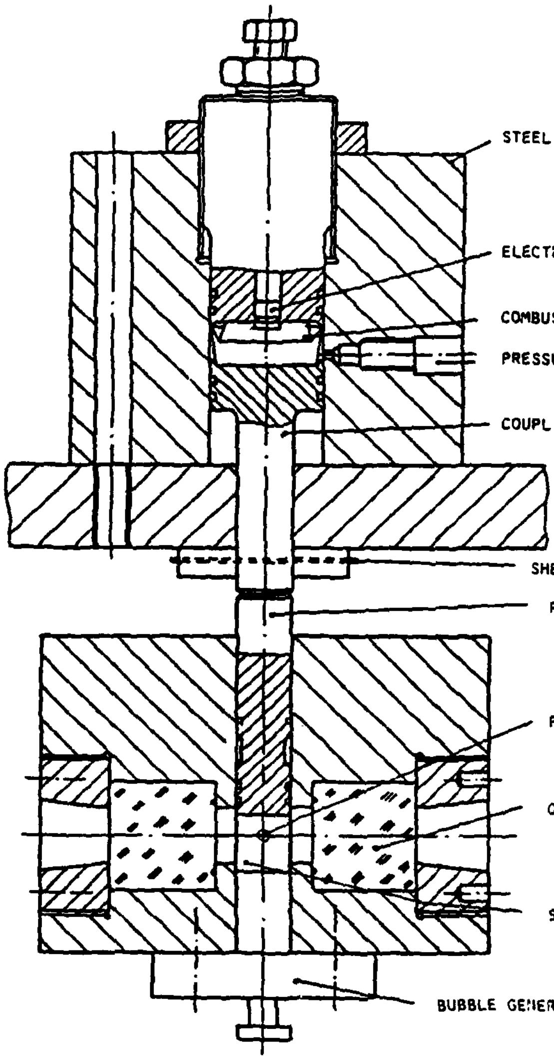


Figure 9. Diagram of the Test Fixture[16]

TABLE 1. SUMMARY OF COMPRESSION IGNITION SENSITIVITY TESTS WITH NOS-365, LP 1845, LP 1846 AND OTTO II

Start-up Curve*	Percent Ullage	Nominal Prepressurization Level	Response Reaction/No. of Tests NOS-365	LP 1845	LP 1846	OTTO II
C	neat	2.3 MPa	0/2	0/3		
C	neat	1.2	0/3	0/2		
D	neat	2.3	0/3	0/2		
D	neat	1.2	0/2	0/2		
E	neat	1.2	0/2	0/2		
C	3.1	2.3			0/6	
C	3.1	1.2	0/2	0/2	2/2	
D	3.1	2.3	0/3	2/5**	2/6	
D	3.1	1.2	3/4	2/3	0/3	2/6
E	3.1	2.3	0/2	3/5	4/9	
E	3.1	1.2	2/3	3/3	0/11	1/1
F	1.4	0.5	0/2			
G	1.4	0.5	1/1			
H	1.4	0.5	1/1			

*Start-up curves C, D and E are characterized by pressure rise rates of 170, 310 and 480 MPa/ms respectively (Reference 13 and 14). Start-up curve F is characterized by pressure rise rates of 25 MPa/ms followed by 95 MPa/ms. Start-up curve G is characterized by a pressure rise rate of 140 MPa/ms. Start-up curve H is characterized by a pressure rise rate of about 400 MPa/ms followed by a rate of about 230 MPa/ms.

**Liquid prepressure for the two ignition events averaged 2.2 MPa which compares with 2.7 MPa for one case with no ignition.

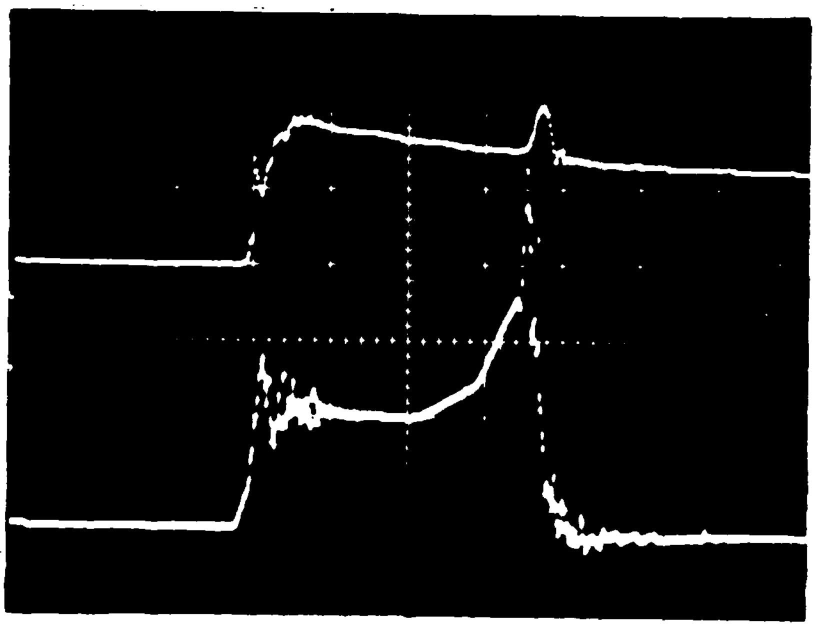


Figure 10. Reaction Initiation of NOS-365[15]

For later tests, the coupling piston between the combustion chamber and the test chamber was modified to permit inserting a plastic assembly and a water barrier next to the test sample. For a test in which the initial pressurization rate was, roughly, 400 MPa/msec followed by a pressurization rate of, roughly, 230 MPa/ msec, Figure 11, there was an ignition. A delayed reaction is again evident. The location of the ignition event is shown in Figure 12 and is located near the bubble generation device shown in Figure 9. Because of the proximity of the reaction to the bubble generation device, a question arises as to whether the observed reaction is due only to adiabatic compression of bubbles or to some other mechanism.

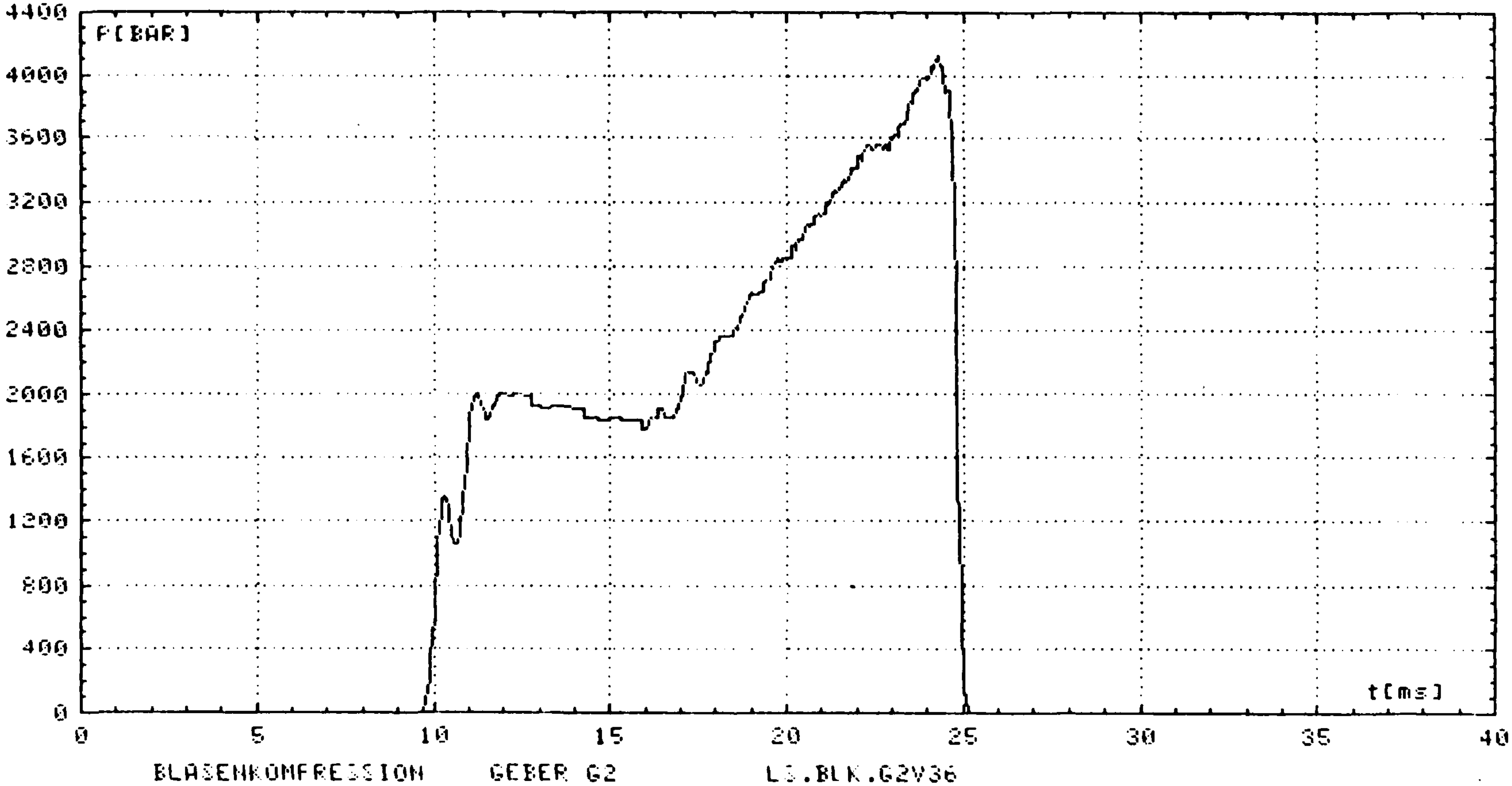
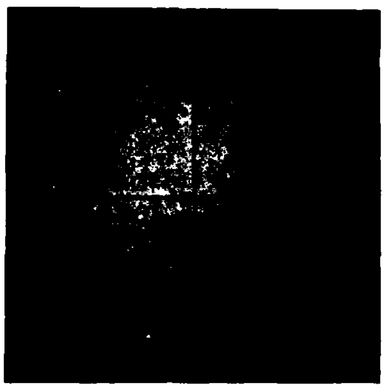


Figure 11. Pressure-Time History for the Ignition Event Illustrated in Figure 12
(Test No. 34-4-84)

Before Compression

0.22 ms



1.0 ms

7.11 ms after
Pressurization

Figure 12. Illustration of an Ignition Event in a Pressurized Cell Containing NOS-365 (Test No. 34-4-84). Times are measured after pressurization. Note the decrease in size of the air bubbles during the pressurization event. The start of reaction is shown in the photo at the lower right and is the black cloud at the bottom of the photo. The black cloud at the top of the photo is due to water flowing around a plastic assembly (see text).

III. CONCLUSION

Extensive evaluations of the sensitivity of various LPs to compression ignition have been conducted at several institutions to identify operational hazards that may be encountered in actual use.[7 17] The early compression ignition tests were directed at determining the ignition/no ignition boundaries of a single bubble when subjected to various pressure conditions. More recent tests have been directed at the response of a bubbly propellant after dynamic loading. It has been shown that the ignition of LPs depends on the amount of ullage present, the bubble size, the rate of pressurization, maximum pressure, and the initial pressure of the liquid.[17] Further studies should address the investigation of pressurized bubbles by optical and IR-devices to obtain a more fundamental understanding of the mechanisms involved. This would be an important step toward the understanding of the compression sensitivity and would support the modeling of an ignition concept. There are five theoretical mechanisms (hot spot,[7] impact (micro-jetting),[7] chemical,[10] cooperative effects,[7] and oscillations[5]) which may be involved during the ignition of a pressurized bubbly LP and it is difficult to say which is the right one. Moreover, if one succeeds in discovering the mechanisms for ignition, adiabatic compression could be considered as a practical ignition source for a liquid propellant gun. Another important unknown parameter in all of the adiabatic compression tests conducted to-date is the amount of dissolved gas in the propellant. For future tests, therefore, gas solubility measurements should be considered.

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[17] W.F. Morrison, J.D. Knapton, I.C. Stobie, J. Mandzy and M. Bulman, "Liquid Propellant Technology," US-German Visit on Liquid Propellant Technology at Ballistic Research Laboratory under DEA-1060, 1983.

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